Transmit Antenna Array Techniques For Cellular CDMA Systems

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ABSTRACT

Adaptive antenna arrays can be employed to improve the transmission quality and thus to increase the capacity of wireless communication systems. In this paper, we address the transmit antenna array techniques for base-to-mobile (downlink) transmission in frequency-division-duplex (FDD) based cellular CDMA systems. A new criterion for transmit weight estimation is developed, which is based upon maximizing the *transmit signal-to-interference-plus-noise ratio (SINR)* and using downlink channel responses estimated by probing-feedback approach. Computer simulations show that the new transmit antenna array technique is effective for improving the capacity of the wireless communication systems.

I. INTRODUCTION

Adaptive antenna array diversity can be used to mitigate the multipath fading effect and to suppress co-channel interference, thus to improve transmission quality and to increase the capacity of the whole wireless communication system [1,2]. In this paper, we focus on the base-to-mobile link (downlink) transmission in cellular CDMA systems. We assume that m antenna elements are equipped in the base station, and d users share the same time and frequency channel within one cell.

Downlink transmission quality can be improved by using transmit diversity techniques for single user case[3-5]. For CDMA systems, each antenna element transmits all the weighted signals to the mobile terminals simultaneously, thus each terminal may receive not only the desired signal component, but also interferences from other undesired signals. *The objective of transmit antenna array techniques is to adjust the transmit weights of the base station antenna elements such that each desired signal arrives at the corresponding mobile user with the SINR being larger than some threshold (quality requirement).*

For FDD based cellular CDMA systems [7,8], since the uplink channel responses and downlink channel responses can be fully different due to independent transmissions, the downlink channel parameters have to be estimated by using probing-feedback approach [3].

In [6], maximum ratio combining (MRC) criterion is used for transmit weight estimation. This approach is very simple, however, it is not an efficient approach in the sense that it cannot provide maximum system capacity. In this paper, we develop a new criterion for transmit weight estimation, which is termed as maximum receive signal-to-interference-plus-noise ratio (MR-SINR) criterion. MR-SINR criterion is obviously better than MRC criterion in terms of system capacity performance, however, the MR-SINR criterion is problematic from the implementation point of view since it involves a difficult nonlinear problem. To solve this problem, we introduce the definition of *transmit SINR*, by which a new maximum transmit SINR (MT-SINR) criterion is developed for transmit weight estimation. Although there is some performance loss as compared with the optimum solution of the MR-SINR criterion, computer simulations show that the new approach can support more users than MRC criterion within one cell with relatively simple computations.

The organization of this paper is as follows. Downlink channel estimation using probing-feedback approach is addressed in Section II. In Section III, MR-SINR criterion for transmit weight estimation is discussed first; then we introduce the concept of transmit SINR, and develop the MT-SINR criterion for transmit weight estimation. The adaptive version of the MT-SINR criterion is given as well. Some system implementation considerations are given in Section IV. In section V, computer simulations are given to demonstrate the capacity improvement of the systems with transmit antenna array as compared to those without antenna array. Also compared are the new technique with MRC criterion. Finally, conclusions are drawn in Section VI.

II. DOWNLINK CHANNEL ESTIMATION

The knowledge of the channel information is important for adaptive antenna array techniques for wireless communications. Suppose the uplink and downlink employs frequency-division-duplex (FDD) transmission mode [7,8], the uplink

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and downlink channel parameters can be fully different due to independent transmissions. Although the uplink channel parameters can be trained and tracked by using training and decision-directed symbols, for downlink transmission, we have to periodically transmit the probing signals from the base-station to all mobile users, and receive feedbacks in order to estimate the downlink channel vectors.

We consider no multipath case in this section, however, the results can be extended to the multipath case directly. Suppose the downlink channel vectors are denoted by $\mathbf{h}_1, \mathbf{h}_2, \cdots, \mathbf{h}_d$, each of which is a $m \times 1$ column vector. Let the probing signals be $p_1(t), p_2(t), \cdots, p_l(t)$ $(l \geq m)$. Theoretically, the probing signals can be either time-orthogonal, frequency-orthogonal, or code-orthogonal. However, in order to use the same philosophy as in CDMA communications, we employs code-orthogonal probing signals.

Let $p_n^{(1)}, p_n^{(2)}, \cdots, p_n^{(l)}$ represent l sets of orthogonal codes (for example, Hadamard-Walsh codes). The probing signals $p_i(t),\ i = 1, 2, \cdots, l$ can be expressed as

$$p_i(t) = \sum_{n=0}^{N-1} p_n^{(i)} c_{T_d}(t - nT_d), \quad i = 1, 2, \cdots, l \tag{1}$$

where $c_{T_d}(t)$ is a continuous waveform function with duration $0 \leq t \leq T_d$. For simplicity, we choose $c_{T_d}(t) = 1$ for $0 \leq t \leq T_d$ and $c_{T_d}(t) = 0$ elsewhere. In the ith antenna $(i = 1, 2, \cdots, m)$, we transmit signal $t_i(t)$:

$$t_i(t) = \sum_{j=1}^{l} v_{ij}^* p_j(t) \tag{2}$$

where * denotes the conjugation operation. Writing in a vector form, we get

$$\mathbf{T}(t) = \mathbf{V}^* \mathbf{P}(t) \tag{3}$$

where

$$\mathbf{T}(t) = [t_1(t), t_2(t), \cdots, t_m(t)]^T \tag{4}$$

$$\mathbf{P}(t) = [p_1(t), p_2(t), \cdots, p_l(t)]^T \tag{5}$$

$$\mathbf{V} = [\mathbf{v}_1, \mathbf{v}_2, \cdots, \mathbf{v}_l] \tag{6}$$

and

$$\mathbf{v}_j = [v_{1j}, v_{2j}, \cdots, v_{mj}]^T \tag{7}$$

The signal received by user k is given by

$$\begin{aligned} r_k(t) &= \sum_{i=1}^{m} h_{ik} t_i(t - \delta_k) \\ &= \sum_{i=1}^{m} \sum_{j_1=1}^{l} h_{ik} v_{ij_1}^* p_{j_1}(t - \delta_k) \end{aligned} \tag{8}$$

Here $\mathbf{h}_k = [h_{1k}, h_{2k}, \cdots, h_{mk}]^T$. Define

$$\begin{aligned} \beta_{jk} &= \frac{1}{N} \int_0^{T_p} r_k(t + \delta_k) p_j(t), \\ & \qquad j = 1, 2, \cdots, l;\ k = 1, 2, \cdots, d \end{aligned} \tag{9}$$

then it is easy to show that

$$\beta_{jk} = \sum_{i=1}^{m} h_{ik} v_{ij}^* = \mathbf{v}_j^H \mathbf{h}_k \tag{10}$$

or

$$\mathbf{V}^H \mathbf{H} = \mathbf{B} \tag{11}$$

where $\mathbf{V} : m \times l, \mathbf{H} : m \times d, \mathbf{B} : l \times d$. Thus

$$\mathbf{H} = (\mathbf{V}\mathbf{V}^H)^{-1} \mathbf{V}\mathbf{B}, \quad \text{if } l \geq m \tag{12}$$

Some parameters are given below:
T_p: probing signal duration;
T_d: chip duration of the probing codes, which can be the same as the code duration of the CDMA data chip duration;
N: $N = T_p/T_d$;
δ_k: time delay;
$\mathbf{V}$: $\|\mathbf{v}_j\| = 1$, for $j = 1, 2, \cdots, l$. One may choose $l = m$ and $\mathbf{V} = \mathbf{I}$, thus obtain $\mathbf{H} = \mathbf{B}$.

III. ALGORITHM FOR TRANSMIT WEIGHT ESTIMATION

Once the downlink channel vectors are obtained, one may use the maximum retion combining (MRC) criteria to determine the transmit weight vectors [6]: $\mathbf{w}_k = \mathbf{h}_k$ for $k = 1, 2, \cdots, d$. The advantage of this criterion is that it does not need any further computations for transmit weight estimation. However, this approach is not efficient in the sense that it cannot support the maximum system capacity.

A. Maximum receive SINR criterion

In this section, maximum receive SINR (MR-SINR) criterion is used for transmit weight estimation. MR-SINR criterion estimates the transmit weights by maximizing the receive SINRs in each mobile receiver simultaneously.

For no multipath case, the measurement signal received by mobile user k is given by

$$r_k(t) = \sum_{j=1}^{d} \mathbf{w}_j^H \mathbf{h}_k s_j(t) + n_k(t) \tag{13}$$

where $n_k(t)$ is additive white Gaussian noise, and $s_j(t)$ is the kth transmitted signal, which can be expressed as

$$s_j(t) = \sqrt{P_j} b_j(t) a_j(t) \tag{14}$$

where $b_j(t)$ and $a_j(t)$ are the jth data signal and spreading signal, respectively. Suppose BPSK modulation is used, then

$$b_j(t) = \sum_{n=-\infty}^{\infty} b_n^{(j)} p_{T_b}(t - nT_b) \tag{15}$$

$$a_j(t) = \sum_{n=-\infty}^{\infty} a_n^{(j)} p_{T_c}(t - nT_c) \tag{16}$$

where the unit rectangular pulse, $p_T(t)$ ($T = T_b$ or $T = T_c$), is defined as $p_T(t) = 1$ for $0 \le t < T$ and $p_T(t) = 0$ otherwise, $L = T_b/T_c$ is the processing gain, $b_n^{(j)}$ and $a_n^{(j)}$ are the jth data symbols and spreading codes.

Assume that signal $s_k(t)$ is supposed to be transmitted to user k. At mobile k, the received signal is first despread by using the kth spreading codes, which yields

$$\begin{aligned} z_k(m) &= \int_{mT_b}^{(m+1)T_b} r_k(t)a_k^*(t)dt \\ &= \sqrt{P_k}\mathbf{w}_k^H\mathbf{h}_k L b_m^{(k)} + \sum_{j=1,j\neq k}^{d} \sqrt{P_j}\mathbf{w}_j^H\mathbf{h}_k \\ &\quad \int_{mT_b}^{(m+1)T_b} b_j(t)a_j(t)a_k^*(t)dt \\ &\quad + \int_{mT_b}^{(m+1)T_b} n_k(t)a_k^*(t)dt \end{aligned} \tag{17}$$

Note that the desired signal component received in user k is $\sqrt{P_k}\mathbf{w}_k^H\mathbf{h}_k L b_m^{(k)}$. If orthogonal codes are used on the downlink for all users within a cell, then for no multipath case, there is no cross correlation between those signals and interference is zero. However, we consider long random PN codes here and assume that there will be cross correlations between those signals. In this case, the energy-per-bit to interference-plus-noise density ratio is [6]

$$\frac{E_b}{I_0 + N_0} = L \times SINR_k^{(R)} \tag{18}$$

where

$$SINR_k^{(R)} = \frac{\mathbf{w}_k^H\mathbf{h}_k\mathbf{h}_k^H\mathbf{w}_k P_k}{\sum_{j=1,j\neq k}^{d} \mathbf{w}_j^H\mathbf{h}_k\mathbf{h}_k^H\mathbf{w}_j P_j}, \quad k = 1, 2, \cdots, d \tag{19}$$

is called the receive signal to interference-plus-noise ratio in user k, and we have ignore the term due to thermal noise.

For multipath case, the received signal at user k is given by

$$r_k(t) = \sum_{j=1}^{d}\sum_{i=1}^{L_k} \mathbf{w}_j^H\mathbf{h}_k^{(i)} s_j(t - \delta_k^{(i)}) + n_k(t) \tag{20}$$

where L_k is the number of paths of signals received at the kth user, and $\mathbf{h}_k^{(i)}$ and $\delta_k^{(i)}$ denote the downlink channel vector and time delay corresponding to the ith path of the signals received at user k, respectively. At mobile terminal k, the despread output of the lth RAKE finger is given by

$$\begin{aligned} z_k^{(l)}(m) &= \int_{mT_b+\delta_k^{(l)}}^{(m+1)T_b+\delta_k^{(l)}} r_k(t)a_k^*(t - \delta_k^{(l)})dt \\ &= \sqrt{P_k}\mathbf{w}_k^H\mathbf{h}_k^{(l)} b_m^{(k)} L \\ &\quad + \int_{mT_b+\delta_k^{(l)}}^{(m+1)T_b+\delta_k^{(l)}} \sum_{j=1,j\neq k}^{d} \sqrt{P_j}\mathbf{w}_j^H\mathbf{h}_k^{(l)} \cdot \\ &\quad b_j(t - \delta_k^{(l)})a_j(t - \delta_k^{(l)})a_k^*(t - \delta_k^{(l)})dt \\ &\quad + \int_{mT_b+\delta_k^{(l)}}^{(m+1)T_b+\delta_k^{(l)}} \sum_{j=1,j\neq k}^{d}\sum_{i=1,i\neq l}^{L_k} \sqrt{P_j}\mathbf{w}_j^H\mathbf{h}_k^{(i)} \cdot \\ &\quad b_j(t - \delta_k^{(l)})a_j(t - \delta_k^{(i)})a_k^*(t - \delta_k^{(l)})dt \\ &\quad + \int_{mT_b+\delta_k^{(l)}}^{(m+1)T_b+\delta_k^{(l)}} n_k(t)a_k^*(t - \delta_k^{(l)})dt \end{aligned} \tag{21}$$

We do not ignore the cross-correlations between different spreading signals arriving at the mobile at the same time, but ignore inter-finger interference and the term due to thermal noise. After coherent combining of the RAKE fingers, the energy-per-bit to interference-plus-noise density ratio is the same as eq.(18), except that $SINR_k^{(R)}$ is replaced by

$$SINR_k^{(R)} = \frac{\mathbf{w}_k^H\mathbf{H}_k\mathbf{H}_k^H\mathbf{w}_k P_k}{\sum_{j=1,j\neq k}^{d} \mathbf{w}_j^H\mathbf{H}_k\mathbf{H}_k^H\mathbf{w}_j P_j}, \quad k = 1, 2, \cdots, d \tag{22}$$

where $\mathbf{H}_k = [\mathbf{h}_k^{(1)}, \mathbf{h}_k^{(2)}, \cdots, \mathbf{h}_k^{(L_k)}]$.

The optimum solution for weight estimation can be obtained by maximizing $SINR_k^{(R)}$ in (19) or (22) for $k = 1, 2, \cdots, d$ simultaneously. However, solving $\mathbf{w}_k$ by maximizing $SINR_k^{(R)}$ involves a very complicated nonlinear programming problem, which requires a good initial guess of the weight vectors, otherwise, the solutions obtained may get into local optima.

B. Maximum transmit SINR criterion

In order to make our algorithm be simple for implementation, we choose the weights by maximizing the power of the desired signal transmitted to the desired user, while minimizing those transmitted to the undesired users. This can be understood by considering that if the power of desired signal is more concentrated on the desired receiver, then less crosstalk powers are induced to the other undesired receivers, thus the other users will receive less interference components, and the SINR at the receiver can be improved.

To simplify the statement; we still use the no multipath case. For multipath case, we may just replace $\mathbf{h}_k$ with $\mathbf{H}_k$. We define the *transmit SINR* for signal k as

$$\begin{aligned} SINR_k^{(T)} &= \frac{\mathbf{w}_k^H\mathbf{h}_k\mathbf{h}_k^H\mathbf{w}_k P_k}{\sum_{j=1,j\neq k}^{d} \mathbf{w}_k^H\mathbf{h}_j\mathbf{h}_j^H\mathbf{w}_k P_k} \\ &= \frac{\mathbf{w}_k^H\mathbf{R}_k\mathbf{w}_k}{\mathbf{w}_k^H\mathbf{Q}_k\mathbf{w}_k} \end{aligned} \tag{23}$$

where $\mathbf{R}_k = \mathbf{h}_k\mathbf{h}_k^H$ and $\mathbf{Q}_k = \sum_{j\neq k}\mathbf{h}_j\mathbf{h}_j^H$. We point out that while the receive SINR is related to the transmit powers of the signals (see eq.(19) and (22)), the transmit SINR is independent of the powers (see eq.(23)). By maximizing $SINR_k^{(T)}$, we may obtain $\mathbf{w}_k$, which is the generalized eigenvector of $(\mathbf{R}_k, \mathbf{Q}_k)$ corresponding to the largest eigenvalue. Therefore, the nonlinear programming problem is now converted into a

generalized eigendecomposition problem. On the other hand, let

$$\mathbf{w}_k^H \mathbf{R}_k \mathbf{w}_k = \lambda \mathbf{w}_k^H \mathbf{Q}_k \mathbf{w}_k \tag{24}$$

where λ is the largest generalized eigenvalue of $(\mathbf{R}_k, \mathbf{Q}_k)$. Denote $\mathbf{Q} = \sum_j \mathbf{h}_j \mathbf{h}_j^H$ then $\mathbf{Q}_k = \mathbf{Q} - \mathbf{R}_k$, thus

$$\mathbf{w}_k^H \mathbf{R}_k \mathbf{w}_k = \lambda \mathbf{w}_k^H (\mathbf{Q} - \mathbf{R}_k) \mathbf{w}_k \tag{25}$$

or

$$\mathbf{w}_k^H \mathbf{R}_k \mathbf{w}_k = \frac{\lambda}{1+\lambda} \mathbf{w}_k^H \mathbf{Q} \mathbf{w}_k \tag{26}$$

Note if λ is the largest generalized eigenvalue of $(\mathbf{R}_k, \mathbf{Q}_k)$, then $\frac{\lambda}{1+\lambda}$ is the largest generalized eigenvalue of $(\mathbf{R}_k, \mathbf{Q})$ as well. Also, In CDMA systems, the user number is usually larger than the antenna element number. If we suppose that the path-gains are sufficiently random such that $\mathbf{Q}$ is a nonsingular matrix with probability one, $\frac{\lambda}{1+\lambda}$ is also the largest eigenvalue of matrix $\mathbf{Q}^{-1}\mathbf{R}_k$. Thus $\mathbf{w}_k$ is just the eigenvector corresponding to the largest eigenvalue of $\mathbf{Q}^{-1}\mathbf{R}_k$. Note that $||\mathbf{w}_k||^2 = 1$ implies that power of signal k is divided to all the transmit antennas, and no additional powers are needed.

C. Adaptive algorithm

Power iterative method is a well known approach for adaptive eigenvector estimation. Our adaptive algorithm for transmit weight estimation is as follows:

$$\mathbf{w}_k^{(t+1)} = \mathbf{Q}^{-1}\mathbf{R}_k \mathbf{w}_k^{(t)} \tag{27}$$

$$\mathbf{w}_k^{(t+1)} = \frac{\mathbf{w}_k^{(t+1)}}{||\mathbf{w}_k^{(t+1)}||} \tag{28}$$

IV. SYSTEM IMPLEMENTATION CONSIDERATIONS

Some system implementation considerations are given below.

A. Feedback rate

The MT-SINR criterion estimates the transmit weights using $\mathbf{h}_k\mathbf{h}_k^H$. Although $\mathbf{h}_k$ changes rapidly due to the movement of the mobile user, $\mathbf{h}_k\mathbf{h}_k^H$ is less fluctuating than $\mathbf{h}_k$ itself [9]. Thus this approach requires much lower feedback rates as compared with those based upon the channel vectors only. Further reduction of the feedback rate can be achieved by replacing $\mathbf{h}_k\mathbf{h}_k^H$ with $\frac{1}{L}\sum_{i=1}^{L}\mathbf{h}_k(t_i)\mathbf{h}_k^H(t_i)$.

B. Frame structure

When downlink channel estimation is needed, probing signals are periodically transmitted from basestation to mobiles, and channel estimates are feedbacked from mobiles to base station. In this case, each slot for downlink contains: Pilot symbols + Probing symbols + ATPC command + Data symbols; while the slot structure for uplink is: Pilot symbols + ATPC command + Mobile feedback + Data symbols.

C. Probing signal transmission mode

Two transmission modes can be used: parallel mode and serial mode.

- *Parallel transmission mode:* The l probing signals are transmitted simultaneously from the base station to the mobiles (the transmitted signal in each transmit antenna is given in eq.(2)). Since each mobile user has the information regarding all the probing signals, β_{jk} for $j = 1, 2, \cdots, l$ in eq.(9) can be estimated one by one via only one correlator in user k. For this mode, since all signal components received from different transmit antenna element arrive at the mobile terminal with the same time delay, this may simplify the hardware implementation.
- *Serial transmission mode:* One probing signal is transmitted in one slot, thus we need l slots to transmit all the probing signals in time-multiplex manner. We assume that the channel parameters are kept the same within the duration of l slots. Based on the received signal in each frame by each user, β_{jk}s can be estimated via a single correlator.

V. COMPUTER SIMULATIONS

We resort computer simulations to evaluate the performance of the adaptive transmit antenna techniques for cellular CDMA systems. We assume that the downlink channel parameters are perfectly estimated, and the multipath numbers for each user are $L_k = 3$ for $k = 1, 2, \cdots, d$. The spreading codes are chosen to be long random PN codes, and the angular spread is 5 degree in cellular macrocell environment. We employ the uinform linear array with antenna spacing $\lambda/2$, where λ is the wavelength at the carrier frequency. Our main objective of the computer simulations is twofold: one is to evaluate the system capacity performance with respect to the transmit antenna numbers; the other is to compare the MRC and MT-SINR criteria. The performance index to be used is *outage probability*, which is defined as the probability of the bit error rate (BER) exceeding a certain threshold P_0 required for acceptable performance. As we know, the BER is related to $\frac{E_b}{I_0+N_0}$ directly. Suppose S is the minimum $\frac{E_b}{I_0+N_0}$ value required to achieve the acceptable performance, the outage probability can be written as

$$\text{Prob}_{out} = \Pr(\text{BER} > P_0) = \Pr(\frac{E_b}{I_0+N_0} < S) \tag{29}$$

Specifically, for downlink transmission, adequate performance ($\text{BER} < 10^{-3}$) is achieved with $\frac{E_b}{I_0+N_0} > 7\text{dB}$.

The performance of the MRC and MT-SINR criteria are compared upon 2000 Monte Carlo runs, which can yield 5×10^{-4} probability resolution. Figure 1 shows the outage probability vs number of antenna elements $M = 1, 2, 4$, where processing gain $L = 32$ and MSINR criterion is used. It is seen that

the system capacity can be obviously improved by increasing the transmit antenna number. From Figure 2 which plots the outage probability vs number of antennas for MRC and MT-SINR criteria, we see that MT-SINR criterion is better than the MRC criterion in the sense that when the former criterion is used, more users can be supported within one cell.

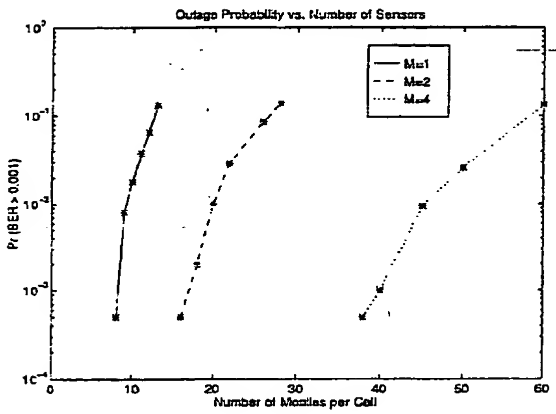

Figure 1: Performance of MSINR for different antenna numbers

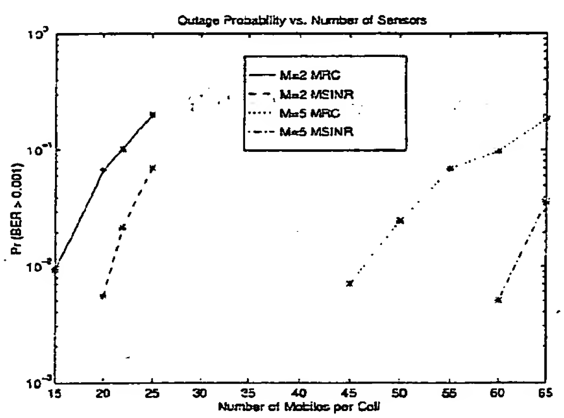

Figure 2: Performance comparisón of MRC and MSINR criterion

VI. CONCLUSIONS

In this paper, we have studied the transmit antenna array technique for wireless wideband CDMA systems. A new maximum transmit SINR criterion for transmit weight estimation is presented which is based upon the knowledge of the downlink channel vectors estimated by using probing-feedback approach. Computer simulations show that transmit antenna array can be used to improve the system capacity, and that the new technique presented in this paper is more efficient than MRC criterion for improving the system capacity performance.

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